Development, Integration, and Utilization of Surface Nuclear Energy Sources for Exploration Missions

Michael G. Houts, George R. Schmidt, Shannon Bragg-Sitton, Robert Hickman, Andy Hissam, Vance Houston, Jim Martin, Omar Mireles, Bob Reid, Todd Schneider, James W. Smith, Eric Stewart, Jason Turpin, Melissa Van Dyke, Jason Vaughn, and David Wagner

NASA MSFC, NP50
MSFC, AL 35812
Tel: (256)544-8136 , Fax: (256)544-6696 , Email:michael.g.houts@nasa.gov

Abstract – *Throughout the past five decades numerous studies have identified nuclear energy as an enhancing or enabling technology for human surface exploration missions. Nuclear energy sources were used to provide electricity on Apollo missions 12, 14, 15, 16, and 17, and on the Mars Viking landers. Nuclear energy sources were used to provide heat on the Pathfinder, Spirit, and Discovery rovers. Scenarios have been proposed that utilize ~1 kWe radioisotope systems for early missions, followed by fission systems in the 10 – 30 kWe range when energy requirements increase. A fission energy source unit size of ~150 kWt has been proposed based on previous lunar and Mars base architecture studies. Such a unit could support both early and advanced bases through a building block approach.*

I. INTRODUCTION

Throughout the past five decades numerous studies have identified nuclear energy as enhancing or enabling for human surface exploration missions [1]. Nuclear energy sources were used to provide electricity on Apollo missions 12, 14, 15, 16, and 17, and on the Mars Viking landers. Nuclear energy sources were used to provide heat on the Mars Pathfinder, Spirit, and Discovery rovers.

Spiral development of surface nuclear systems could be accomplished by "spiraling" off systems that have previously flown or are under development. For example, highly efficient power conversion units developed under the Stirling Radioisotope Generator program (Spiral 1) could be scaled up to enable kWe-class nuclear radioisotope systems with significant fuel savings (Spiral 2). Much of the system's balance of plant (heat transport, power conversion, power processing, structure, radiators, etc.) for a 10-30 kWe-class fission surface energy source could then be directly evolved from the 1 kWe-class radioisotope system (Spiral 3) [2].

Surface fission reactors could also be highly analogous to reactors previously flown in space. For example, the former Soviet Union flew 31 BUK reactors with a coolant outlet temperature of 975 K and a power rating of 100 kWt

[3]. The coolant outlet temperature and power rating of the BUK could be ideal for surface energy sources using Stirling (or other high efficiency) power conversion. The lifetime requirement for a surface fission energy source would likely be longer than that of the BUK flight system. However, the surface system will still have relatively low fast neutron fluence and fuel burnup, potentially mitigating nuclear development concerns compared with longer-life, higher power fission systems. Although a different reactor would likely be designed and developed for surface energy source applications, the 31 successful flights of the BUK system at a temperature and power level applicable to surface fission energy sources provides somewhat of a "Spiral 1" analogue for surface fission energy sources.

In addition to the BUK reactor flights, the former Soviet Union flew two TOPAZ reactors. One of the TOPAZ reactors operated for a year in space at a power level of 150 kWt. The use of in-core thermionic power conversion eliminated the need to run the NaK coolant at the highest possible temperature. However, the demonstrated core exit temperature would still be adequate for some power conversion options.

The United States flew the SNAP-10A (System for Nuclear Auxiliary Power) reactor in 1965. In addition to the SNAP-10A flight, several SNAP reactors were tested

on the ground. The S8ER operated for 100 days at 600 kWt and an outlet temperature of 975 K, and 365 days at greater than 400 kWt and an outlet temperature of 975 K [4]. The reactor outlet temperature demonstrated in these tests is adequate for surface energy applications. S8ER thermal power was a factor of 3-4 higher than needed for surface applications. Demonstrated lifetime was a factor of 2-3 lower than desired for surface nuclear energy applications, but no fundamental reasons have been identified that would preclude similar cores from operating > 3 years.

One fundamental difference between the SNAP-10A and TOPAZ reactors and the BUK reactors was that the SNAP-10A and TOPAZ systems were moderated, whereas the BUK reactors were fast spectrum. Moderated fission systems may not be attractive for applications requiring greater than 1000 kWt [5]. However, in the power range of interest for surface fission systems (typically 100 – 200 kWt) moderated systems offer at least three potential advantages:

1. All operational commercial, defense, university, and test reactors in the United States are moderated. Ongoing US operational experience is with moderated systems, and in-pile testing needed for development of a moderated system may be viable in the US because of available test facilities.

2. The use of a moderated system reduces fast flux and radiation damage concerns compared to a fast-spectrum system with similar requirements.

3. The use of a moderated system may eliminate the need for highly enriched uranium (HEU) fuel. Eliminating the need for HEU could reduce cost and schedule associated with meeting safeguard requirements and could potentially reduce programmatic risk [6].

In summary, it appears that the surface fission reactor designer will have numerous potential options, some of which are analogous to fission systems that have already flown in space. These previously flown systems could serve as "Spiral 1" for fission surface reactor development.

Although planetary surface fission energy system balance-of-plant components can potentially evolve from those used on surface radioisotope energy systems, and the fission reactors themselves can potentially benefit from designs that have already flown in space, significant issues remain. For example, additional adaptations will be required, and unique integration and operational issues will exist. Specific adaptation, integration, and operational issues include the following.

1. Integration of energy source with lander. Issues include structural support during launch, landing, and operation; thermal management (heat load from radiators, hot surfaces, radiation); radiation issues (shielding, effect on residual propellant); emplacement and deployment of the energy source; and others.

2. For lunar missions, will the energy source launch, land, and start during daylight? If not, extremely cold temperatures may need to be endured.

3. For lunar missions, will peak power be required at all times? Solar loading on radiator panels may increase radiator temperature and decrease efficiency during the lunar day.

4. Will the system operate at full power at all times, or will power be reduced (possibly shutdown) when the crew is absent?

5. What is the desired ratio of process heat energy to electrical energy? What is the desired temperature for process heat?

6. Long-term effects of high thermal loading on the lunar or Martian regolith will need to be quantified. Regolith temperature near the lander/radiators could increase by ~100 K (or more) within the first few days of energy source operation.

7. Long-term effects of ionizing radiation on the lunar or Martian regolith (e.g. regolith charging) will need to be quantified.

8. Radiator design, including deployment (if needed) on the planetary surface, minimizing negative effects from dust and from incident solar radiation.

9. Optimal radiation shielding approach for robotic and human missions. Options include bringing all shielding from earth (potentially optimal for robotic missions) and using a split approach where some shielding is brought from earth and regolith is used to provide the remainder (potentially optimal for human missions). The ability to perform precision landings and the choice of landing sites may also affect shield design.

10. Choice of lander propellant combinations. General capability of lander.

11. Infrastructure assumptions. Will any power be available prior to the emplacement of the reactor? Will the capability exist to move regolith? Will the capability exist to drill / dig holes?

12. Human rating requirements. Will the lander be human rated throughout all mission phases, or only as needed to support energy source operation following a successful landing?

13. Energy source specifics, including desired heat rejection temperature, neutron and gamma flux at system boundary, requirements associated with exposed materials, unique requirements (i.e. stability to allow power beaming to rovers, transport of thermal energy to support In-Situ Resource Utilization), and others.

II. ENERGY SOURCE TECHNOLOGY CHOICES

The choice of energy source technologies would be affected by numerous factors. Even if an energy source

optimized for planetary surface applications is chosen, there will be a significant benefit from utilizing the experience, infrastructure, expertise, and fundamental technologies developed in previous and ongoing space nuclear programs (both radioisotope and fission).

Considerable mass savings could be achieved by using lunar or Martian regolith to provide gamma shielding for the planetary surface fission energy source. However, regolith is a very good insulator, and components or subsystems that are surrounded by it will not be able to effectively reject heat to the planetary surface environment. The design of radial reflectors, control systems, neutron shields, and other components will need to provide for some other means of heat rejection.

The ~30 kWe reactor that would be well suited for surface applications could potentially be used on other exploration missions. For example, the 30 kWe system would have adequate power to provide crew power during earth-Mars transits [7] or power for cryo-cooling a propellant depot in orbit around Mars (either LOX or LH_2 for chemical or LH_2 for nuclear thermal). Thus, it may be desirable for the reactor to be able to operate independent of gravity. However, for surface applications it may be acceptable to take advantage of gravity in other parts of the system (i.e. thermal coupling, heat rejection), provided that the balance-of-plant components can be redesigned to allow use in microgravity.

Compatibility with planetary surface environments may also be a concern. Ideally, all potentially exposed materials should be compatible. Dust would be a concern, and steps must be taken to ensure that exposure to dust does not cause unacceptable corrosion or have unacceptable effects on the reactor control system or any other system with moving parts.

Human missions will require significantly more radiation shielding than robotic missions. One potentially desirable option is to design surface fission energy sources to meet robotic mission shielding requirements. Ideally, regolith could then be used to provide any additional shielding that would be required to use the energy source on a human mission. Methods for burying the reactor portion of the energy source or otherwise using regolith to provide gamma shielding would need to be devised.

III. ONGOING SURFACE NUCLEAR ENERGY SOURCE RESEARCH

III.A. System Integration

A systems integration study has been initiated to identify and resolve key issues associated with integrating a planetary surface lander with a surface fission energy source. Results of the study will be used to design and develop a realistic, useful breadboard for experiments related to surface system integration.

III.B. Regolith as Radiation Shielding

Shielding work has been initiated that assumes a reactor design similar to that of the Russian "BUK" space reactor. Detailed Monte Carlo analysis is being performed to assess the shielding effectiveness of regolith and combined hydride/regolith shields for neutrons and gammas emitted from the reactor. Effects such as regolith heating and regolith activation are also being calculated. The BUK is a fast-spectrum system, and neutron shielding requirements will be higher for it than for a similarly-sized moderated system. For the purposes of this paper, no additional detail associated with the reactor design is required.

Calculations have shown that > 4 m of regolith are required to shield a typical surface fission energy source to a level of ~2 rem/year at a distance of 100 m [8]. In addition, if very little neutron shielding is brought from Earth, neutron scatter within the regolith will require that the reactor be buried at depths >1 m with very few streaming paths in order to meet surface dose requirements (for the purposes of this study <5 rem/year) at ~100 m. The thickness of shielding can be greatly reduced if some neutron shielding is brought from earth, or if hydrogenous material (i.e. water) is incorporated into the regolith shielding.

III.C. Waste Heat Rejection

For the most part, terrestrial nuclear power plants reject waste heat through convective water cooling. Because of the planetary surface environment, surface nuclear energy sources on both the Moon and Mars cannot reject waste heat using a similar technique. The only technique available in a space (vacuum) environment is through radiative heat transfer which requires a large surface area to reject the required heat load and materials with high emissivity. Because of the large temperature swings on the Lunar surface (~ 100 K at night and up to ~390 K during the day) and the Martian surface, trying to radiate heat with such large ambient temperature variations is inefficient. The goal of this effort is to test various combinations of materials (with varying emissivity values) to maintain a constant radiator temperature. Also, because the temperature dependence of emissivity is an important piece of data in evaluating this whole process, a by-product of the test set-up is the capability to measure the emissivity of radiator materials at elevated temperatures.

A surface heat rejection sub-system test chamber has been developed with the capability to both heat candidate radiator sample panels and irradiate them with simulated solar energy. Figure 1 is a picture of the surface heat rejection sub-system test chamber at NASA's Marshall Space Flight Center (MSFC) in Huntsville, AL. Sample radiator panels are suspended in the chamber where they are attached to a heat block simulating the output of a standard surface nuclear energy system. The samples are then illuminated with an X-25 solar simulator operating between 0.5 and 6 equivalent solar constants. Sample radiator panel temperatures are measured to determine the effectiveness of the sample radiator materials to radiate to the ambient environment.
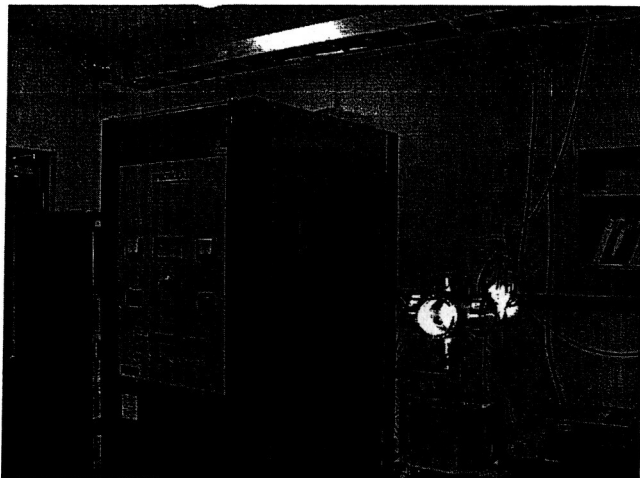

Figure 1. Surface Heat Rejection Performance Test Chamber with X-25 Solar Simulator.

Figure 2 shows a more detailed view of the radiator sample material configuration. Typically, the radiator sample material is mounted to a heat block with an upper temperature capability of 1100 K, but most of the testing for this study will concentrate in the 300 to 500 K range. Early testing was done with a standard stainless steel sample both for the ease of acquisition and its high temperature application. However, future tests are planned on a more targeted class of radiator materials.
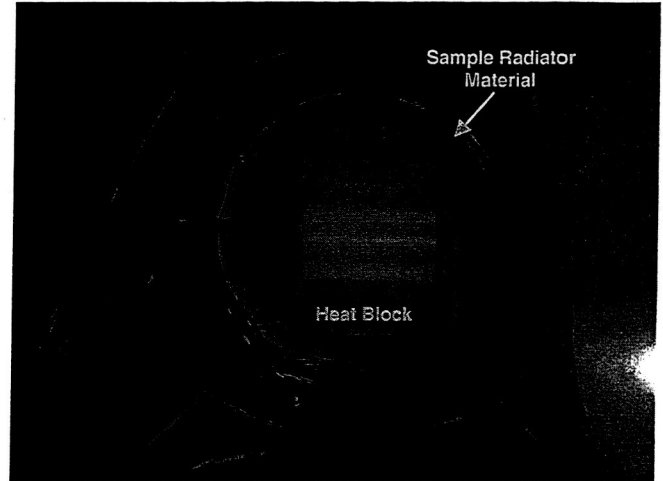
Figure 2. Surface Energy Heat Source for Evaluating Heat Rejection Techniques

Typical data collected during the check-out phase of this study to determine the overall capability of the test system are shown in Figure 3. During this test the solar simulator illuminated the stainless steel sample material at about 2 equivalent suns. The data in Figure 3 show that during the period of time when only the solar simulator was irradiating the sample, the temperature rose from 293 K to 420 K. When 60 W was applied to the heat block, the final temperature measured was about 630 K, and finally with heaters operating at 120 W the final temperature measured was 810 K. This initial test was able to prove the system to 800 K, but with further improvements, the system capability has been increased to 1100 K. Due to the success of the early check-out tests, radiator materials will be exposed in the facility in the near future to evaluate their capability to efficiently radiate the waste heat from a nuclear surface energy system .
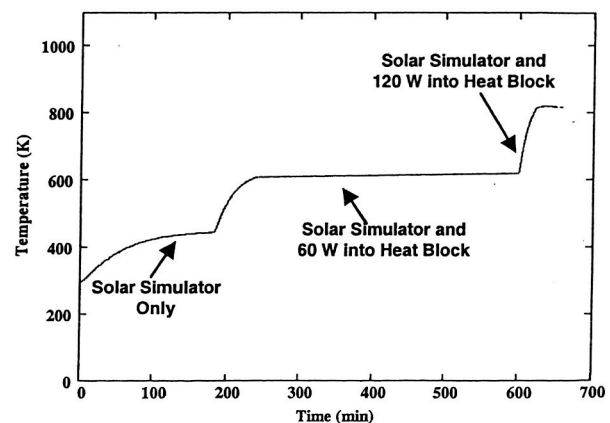
Figure 3. Typical Temperature Data Showing Test System Capability

III.D. Surface Environmental Effects on Integrated System

The lunar or Martian environment will affect the integrated surface fission energy source. A theoretical and experimental program has been initiated to investigate changes in microstructure and material properties as a function of exposure time to various environments.

Refractory and non-refractory candidate alloys are being subjected to representative planetary surface conditions. These include temperatures (up to 1773 K), ultra-high vacuum (10^{-9} Torr) or Martian atmosphere, and contact with simulated lunar or Martian regolith (JSC-1 and JSC MARS-1, Figure 4). In the future, charging effects from the ionizing environment may also be included.

After exposure, material coupons will undergo room temperature mechanical strength testing and materials characterization analyses. Based on any undesirable change in material properties, mitigation techniques will be developed to improve the resistance of these materials to their operating environments. Such mitigation techniques can include the application of functionally gradient materials (FGM) in which barrier coatings are gradually applied via plasma spray, and the charging of surfaces to repel dust and minimize adhesion. As with all tasks, a thorough literature review is being performed to ensure that there is no duplication of previous research. This work will be done in an iterative manner, initially exposing coupons to only one condition with the long term goal of applying multiple conditions simultaneously to observe complex, multi-mechanism material degradation processes.
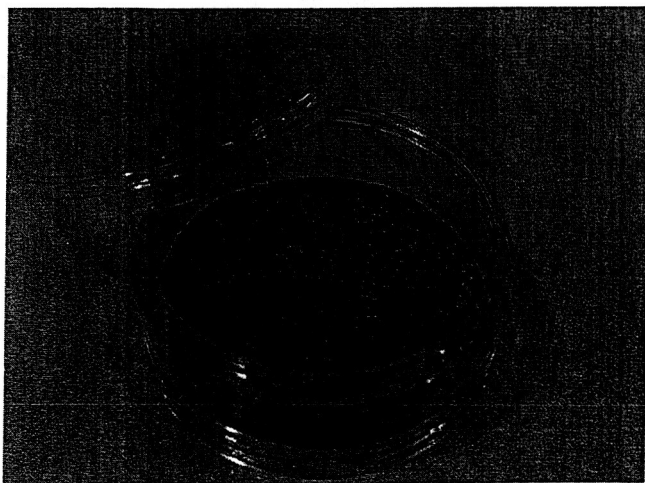

Figure 4. JSC MARS-1 Regolith Simulant

III.E. GPHS Module Thermal Simulators

One potential spiral development path for fission surface energy sources would involve first developing radioisotope systems in the ~1 kWe power range. The approach would be to use radioisotope systems to the maximum extent practical, limited by the availability of Pu-238. Structure, thermal management, power processing, and power conversion systems developed in support of Spiral 1 and Spiral 2 radioisotope systems could directly evolve for use in fission surface energy sources in Spiral 3.

Effective design and development of relatively high power (~1 kWe) surface radioisotope systems will require the use of high fidelity, non-nuclear thermal simulators that simulate the thermal output of a General Purpose Heat Source (GPHS) Module. These thermal simulators will be used to test various configurations and integration techniques. Development of GPHS module thermal simulators is ongoing, with initial simulators anticipated to be available by the end of 2005. GPHS module thermal simulator development work is building on the highly successful fission system thermal simulator work performed at Marshall Space Flight Center's (MSFC) Early Flight Fission Test Facility (EFF-TF) [9].

III.F. Surface System Integration / Interface / Interaction Testing

Utilization of fission energy sources would require that they be effectively integrated with the remainder of the surface system. This theoretical and experimental task is to investigate subsystem integration issues. Specific issues include integrating the fission energy source with a power conversion subsystem, investigating control of integrated subsystems, investigating transient behavior of integrated subsystems, and investigating the behavior of integrated subsystems during off-normal conditions. Issues associated with using a fission energy source to provide energy to multiple loads are also being investigated.

In one planned experiment, a simulated gas-cooled reactor and closed-loop Brayton cycle will be integrated and tested. A closed-loop Brayton cycle powered by a fission reactor offers an attractive option for nuclear-based planetary and space electric power. The testing program combines an existing MSFC simulated reactor and an existing Sandia National Laboratory (SNL) Brayton cycle. Since the electric heater used in the SNL Brayton was not intended to mimic the dynamic response of a fission reactor, replacing it with the MSFC simulated reactor results in a system more prototypic of an actual system. The use of existing hardware allows for initiation of early testing to determine the operational behavior of this combined system. Test results can be used to validate

dynamic models and support more advanced follow-on hardware evaluations.
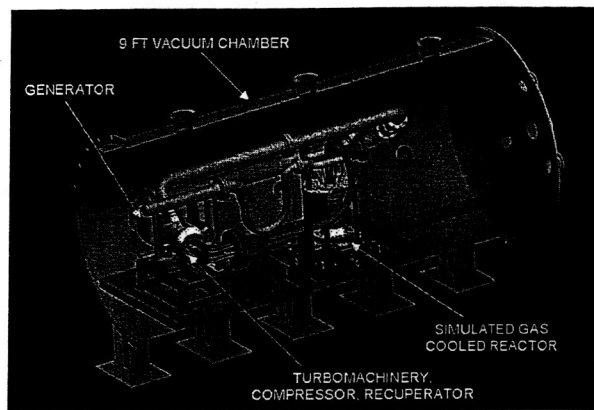
Figure 5. Preliminary Layout for Simulated Gas-Cooled Reactor /Brayton Cycle Testing.

III.G. End-to-End Breadboard Development

Work has been initiated to develop an end-to-end breadboard to investigate system-level integration and operational issues associated with a fission surface energy source and relatively high power (~1 kWe) surface radioisotope systems. Upon completion the breadboard will include highly realistic non-nuclear thermal simulators, multiple options for primary heat transport, multiple options for power conversion, power management and distribution, a thermal management and a waste heat rejection system. The breadboard will be focused towards resolving key integration issues. Nuclear system breadboard testing has been used in the past to help resolve key system design and integration issues [10]. Non-nuclear breadboard testing of a potential fission energy source coupled to a Stirling power conversion subsystem is shown in Figure 6.
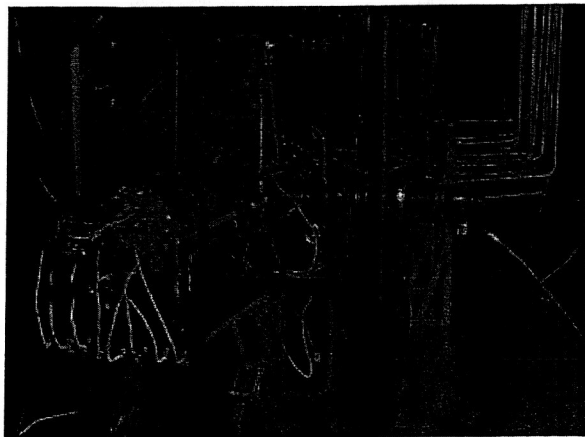
Figure 6. Non-nuclear coupled heat source / power converter breadboard testing.

III.H. Advanced Materials Development

High temperature materials research and development could be of benefit to Lunar and Martian fission energy sources. Typical refractory metal alloys for high temperature space components are unsuitable for structural applications due to oxygen embrittlement. However, Mo-Re alloys exhibit lower mass gains in Mars-relevant environment due to low O solubility as compared to Niobium (Nb) and Tantalum (Ta) alloys. Oxidation resistant high chromium content steel and nickel base alloys are commercially available but are mainly suitable for lower temperature applications. Lack of extensive test data and availability of suitable alloys for high temperature and potentially corrosive environments place the current refractory materials at a low technical readiness level (TRL). More work is needed before these materials can be applied to long-term surface and portable energy applications using fission and radioisotope energy sources.

Facilities at the MSFC Propulsion Research Laboratory are being used to investigate materials in a simulated Mars environment. Tests are being conducted with a simulated Mars atmosphere (95% CO_2 with trace gases, including nitrogen, argon, oxygen, carbon monoxide, water, methane, and others). During these tests, inspection of coupons and specimens are performed with destructive evaluation (DE) methods such as tensile, bend (DBTT), microstructure, and composition (C, H, N, O, etc.). The testing will also include long-term thermal creep behavior and relevant aspects of the fabrication that are susceptible to corrosion failure such as welding.

Specific tasks, to date, have included:

1. Selection and procurement of commercial material samples such as stainless steels, oxide dispersion strengthened Fe and Ni alloys, and Mo-based refractory metal alloys.
2. Hardware fixture and adaptation of facilities to conduct testing at temperatures up to or exceeding 1473K at various pressure levels (vacuum to 1 atmosphere).
3. Testing and metallographic characterization of material samples.
4. Establishing potential mechanisms for degradation (theory/models).
5. Refractory metal or other high temperature alloy development to improve oxidation and corrosion resistance without sacrificing strength, ductility, and fabricability.

Future efforts will include investigation of potential radiation effects on candidate materials.

III.I. Low Melting Point Coolants

Low melting point coolants (m.p. < 250K) with adequate high-temperature operating capability and radiation damage resistance can extend the temperature range under which a surface nuclear energy system can be cold started without requiring freeze/thaw capability. Liquid metal eutectics and silicone heat transfer fluids are potential coolants, depending on environment and system configuration, and three candidates have been identified. Research and testing through the remainder of 2005 will investigate issues associated with compatibility, high temperature operation, stability, thermal hydraulic performance, and other parameters of interest.

Advanced coolants could improve several aspects of surface nuclear energy system design. Applications include primary heat transport (reactor or radioisotope to power converter), transferring heat energy for ISRU, waste heat rejection, payload thermal management, and others.

III.J. Planetary Surface System Thermal Management and Control

An integrated thermal model of the surface fission energy source, associated equipment, the lander, and the surrounding planetary environment needs to be developed. Thermal effects of the energy source on regolith temperatures, lander thermal management, and base thermal management need to be quantified. Thermal effects of burying the reactor are also being investigated. The effectiveness and desirability of potential radiator configurations are being assessed. Radiating capability as a function of "time" (i.e. incident angle of sun) is being calculated for various potential configurations. Results associated with steady-state and transient lunar base operation will be available later this year.

IV. CONCLUSIONS

Throughout the past five decades numerous studies have identified nuclear energy as enhancing or enabling for human surface exploration missions. Nuclear energy sources were used to provide electricity on Apollo missions 12, 14, 15, 16, and 17, and on the Mars Viking landers. Nuclear energy sources were used to provide heat on the Mars Pathfinder, Spirit, and Discovery rovers.

Spiral development of surface nuclear energy systems can help enable the Vision for Space Exploration. Work has been initiated to help ensure the timely availability of these systems.

ACKNOWLEDGMENTS

NOMENCLATURE

ISRU   In-Situ Resource Utilization

REFERENCES

1. V. Houston, "Surface Power Study Kickoff Meeting,", NASA MSFC, MSFC, AL (2004).

2. G. R. Schmidt, et al. "NASA's Program for Radioisotope Power System Research and Development," Proceedings of Space Technology and Applications International Forum – STAIF 2005, AIP Conference Proceedings Volume 746, ISBN 0-7354-0231-0, pp. 429-436, American Institute of Physics, M. S. El-Genk ed. (2005).

3. N. N. Ponomarev-Stepnoi, "Russian Space Nuclear Power and Nuclear Thermal Propulsion Systems," Nuclear News, December, 2000, pg 33 (2000).

4. J. A. Angelo, Jr. and D. Buden, *Space Nuclear Power*, pg 170, Orbit Book Company, Malabar, FL (1985).

5. D. I. Poston, "A Comparison of Fast-Spectrum and Moderated Space Fission Reactors," Proceedings of Space Technology and Applications International Forum – STAIF 2005, AIP Conference Proceedings Volume 746, ISBN 0-7354-0231-0, pp. 859-867, American Institute of Physics, M. S. El-Genk ed. (2005).

6. P. G. Edelmann, "Determination and Assessment of Graded Safeguards Categories for Potential Space Reactor Fuels," Proceedings of Space Technology and Applications International Forum – STAIF 2005, AIP Conference Proceedings Volume 746, ISBN 0-7354-0231-0, pp. 815-819, American Institute of Physics, M. S. El-Genk ed. (2005).

7. S. K. Borowski, L.A. Dudzinski, and M. McGuire, "Bimodal Nuclear Thermal Rocket Propulsion for Power-Rich, Artificial Gravity Human Exploration

Missions to Mars," *52ⁿᵈ International Astronautical Congress, 2001,* Toulouse, France, IAA-01-IAA-01-IAA.13.3.05.

8. M. G. Houts et al., "Planetary Surface Reactor Shielding Using Indigenous Materials," Proceedings of Space Technology and Applications International Forum – STAIF 1999, AIP Conference Proceedings Volume 458, ISBN 1-56396-846-0, pp. 1476-1479, American Institute of Physics, M. S. El-Genk ed. (1999).

9. M. K. Van Dyke, "Hardware Progress Made in the Early Flight Fission Test Facility (EFF-TF) to Support Near-Term Space Fission Systems," Proceedings of Space Technology and Applications International Forum – STAIF 2005, AIP Conference Proceedings Volume 746, ISBN 0-7354-0231-0, pp. 895-902, American Institute of Physics, M. S. El-Genk ed. (2005).

10. I. Hrbud, et al. "End-to-End Demonstrator of the Safe Affordable Fission Engine (SAFE) 30: Power Conversion and Ion Engine Operation," Proceedings of Space Technology and Applications International Forum – STAIF 2002, AIP Conference Proceedings Volume 608, ISBN 0-7354-0053-9, pp. 906-911, American Institute of Physics, M. S. El-Genk ed. (2002).